MEASUREMENTS OF LOW ENERGY NEUTRAL HYDROGEN OUTFLUX DURING ICRF HEATING

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Using the Low Energy Neutral Atom Spectrometer, measurements were made of the H° and D° outflux from PLT during ion cyclotron heating experiments. In the energy range $20<E<2000$ eV, the application of rf power at frequencies appropriate to fundamental and 2^{nd}-harmonic heating, results in a rapid rise in the charge exchange outflux at a rate of about 10^{15} cm^{-2} s^{-1} MW^{-1}. This flux increases linearly with rf power and inversely with plasma current. The cause of this flux and its impact on plasma behavior are discussed.

Introduction

Plasma heating by the application of radio-frequency power in the ion-cyclotron-range-of-frequencies (ICRF) is the main research effort on the PLT tokamak.[1] The experiments include investigations of heating versus plasma parameters, of antennae configurations to couple wave energy into the plasma, and of methods to control the behavior of the heated plasmas.

One diagnostic that has special utility in characterizing ICRF-heated plasmas is the Low Energy Neutral Atom Spectrometer[2] (LENS). This device detects hydrogen (or deuterium) atoms that are emitted from the plasma by neutralization processes, the main one of which is charge exchange. Because of the LENS' sensitivity to low energy particles, it is used to study edge plasma behavior. This is important to ICRF plasmas because the coupling between antennae and the plasma occurs through the plasma edge.

Other techniques can be used to study low energy neutral hydrogen emission, but the LENS is better suited overall. Surface probes[3,4,5] suffer from poor energy and time resolution. Spectroscopic diagnostics usually do not work at temperatures above ~ 100 eV; and standard stripping cell techniques[6,7] do not work well below 500 eV. Recently electron attachment cells have been developed and used[8] in the energy range $10 < E < 1000$ eV. These suffer from poor sensitivity, hence poor time resolution. The secondary-electron emission, time-of-flight system employed in the LENS diagnostic overcomes all the above limitations, giving it an energy range of $5 < E < 2000$ eV and a time resolution of $\tau \gtrsim 200$ μs. The LENS on PLT has been used for 4 years. Other LENS systems[9,10] have been recently assembled and will soon produce necessary data for inter-machine comparisons. At present, however, the data from PLT stand out as the most thorough and systematic investigations of low energy neutral behavior. Studies have already been published on discharge cleaning[11] and ohmic plasmas.[12] Unpublished reports[13] and abstracted[14] papers have been presented on beam heated, ICRF-heated and lower hybrid driven plasmas. The aim of this paper is to give the most up-to-date review of low energy neutral atom emission from ICRF heated plasmas.

Apparatus

The PLT tokamak is a mid-sized device with the following baseline parameters:

$$R = 132 \text{ cm},$$

$$a = 40 \text{ cm},$$

$$I_p(\text{max}) \simeq 700 \text{ kA},$$

$$n_e(\text{max}) \simeq 10^{14} \text{ cm}^{-3},$$

$$B_T(\text{max}) \simeq 40 \text{ kG}$$

The toroidal magnetic field is chosen to match the appropriate cyclotron resonance of the desired ion. The two rf generators available for these experiments had f = 25 and 42 MHz. The lower frequency was used for the He^3 and H-minority regimes at $B_T \sim 25$ and 17 kG respectively, while the higher frequency provided heating in the H-minority and H-2nd harmonic regimes at $B_T \sim 28$ and 14 kG respectively. The rf power was coupled into the plasma via pairs of half-turn antennae. The main limiters[15] for these experiments were located at one toroidal position and were top-bottom mushrooms and in-out 1/4-turn rings. An auxiliary movable limiter was located 100° away toroidally in the CCW direction. It is top mounted (figure 1).

The LENS diagnostic has already been described in detail elsewhere.[2] In short, the LENS uses time-of-flight to energy discriminate particles which are detected by secondary electron emission from a Be-Cu plate. Calibrations have been made in the laboratory and in PLT and generally agree to within ± 30%. Recent improvements have been made[16] which increased the signal to noise ratio by 15.

The LENS views the PLT plasma through the midplane at the same toroidal location as the auxiliary limiter.

Results

Measurements were made during D-He^3 and H-D operation. The data shown in detail are for D-He^3 but the results apply to both.

The evolution of the neutral emission, Γ, integrated over the energy range 25-1000 eV, is shown in Fig. 2 for two discharges: one with, and the other without, ICRF heating. These data are for the case of the auxiliary limiter withdrawn from the plasma. The initiation and termination of the discharges are identical in both discharges. The initiation and termination are also similar to the thousands of other ohmically-heated discharges monitored by the LENS. A major difference is seen during the application of ICRF power. The total flux increases sharply. To within the time resolution of the LENS, ~ 200 μs, the rise in Γ is instantaneous. At the end of the ICRF heating pulse, Γ drops about a factor of 5 in 1 ms. Frequently the flux remains constant at this new higher level throughout the ICRF heating pulse. The line averaged electron density, $\bar{n}_e$, was about $2\times10^{13}cm^{-3}$ before the 100-

150 ms long ICRF heating up. During the pulse it rose slowly about 30%. Programming $\bar{n}_e$ to behave in this fashion (without ICRF) resulted in no change to the LENS signal. There are also cases where, though the ICRF power is constant, the flux drops ~50%. This may be due to impurity influx which is known[17] to reduce the charge-exchange outflux. During these cases, when Γ drops during the ICRF pulse, impurity radiation, particularly from carbon, is seen to increase. As shown in Fig. 3 and 4, the rise in Γ is not uniform at all energies measured. A proportionally higher Γ is seen at $25 < E < 50$ eV than at $50 < E < 500$ eV. Another way of seeing this effect is to examine the average energy, $\bar{E}$, of the particles detected by the LENS. Prior to ICRF, $\bar{E}$ is generally 250-400 eV. During ICRF $\bar{E}$ can drop 30%.

The increase in D° efflux, $\Delta\Gamma$, was measured as a function of power. Up to ~ 1.5 MW, $\Delta\Gamma$ increased linearly with applied power (Fig. 5) at a rate of 4×10^{14} $cm^{-2} \cdot s^{-1} \cdot MW^{-1}$ for a plasma current of 520 kA. H-D plasmas generally showed a twice higher rate than D-He^3 plasmas. Above 2 MW there was a tendency for $\Delta\Gamma$ to saturate. Part of this behavior may be attributed to non-reproducible or poor coupling of the antennae to the plasma.

The variation of $\Delta\Gamma$ with plasma current was determined for the range $150 < I_p < 500$ kA. $\Delta\Gamma$ increased with decreasing current. The variation was sigmoidal in shape (Fig. 6) with the point of inflection at ~ 300 kA. Ohmically heated plasmas show no variation in Γ with I_p, i.e., $\Delta\Gamma < 10^{13} cm^{-2} s^{-1}$

Inserting the auxiliary limiter into PLT results in a reduction of about 25% of the power to the other limiters. It also causes up to a 30-fold increase in Γ seen by the LENS, depending on the minor radius of the auxiliary limiter. It is possible the even more severe toroidal poloidal asymmetries exist. Figure 7 shows Γ for two different ICRF heated discharges: one with the auxiliary limiter in, and the other with it out. For this case, a 5-fold increase in Γ was seen in the steady-state (150-400 ms) portion of the discharge prior to ICRF. As shown in this figure, $\Delta\Gamma$ during ICRF is approximately independent of proximity to the limiter.

Discussion

The application of ICRF power to PLT results in an increase in the central ion temperature. In contrast, the LENS data show a decrease in the edge ion temperature. The flux spectra shown in Fig. 3 and 4 cannot be fit by a single temperature Maxwellian. However, using a code to model the efflux spectra, the edge ion temperature, $T_i(a)$, can be extracted. As a rule of thumb, $T_i(a)$ equals the location of the low energy peak in $d\Gamma/dE$. From this guide and the more detailed computer model, it is seen that $T_i(a)$ drops from ~60 eV to less than 25 eV. A decrease in $T_i(a)$ during ICRF has been reported earlier[18] on ATC. The cause of this decrease in $T_i(a)$ is not known. It may be an increase in thermal conductivity or radiation and ionization losses from hydrogen or impurities. It should be noted that though $\bar{E}$ and $T_i(a)$ drop, the increase in Γ increases the charge exchange sputtering away from the limiter a factor of ~5 to ~10^{13} $cm^{-2}s^{-1}$.

ICRF heating also causes an increase in $\bar{n}_e$ (unless the torus walls are heavily gettered) and an increase in Γ. Two questions naturally arise; (1) is $\Delta\Gamma$ the cause or the effect of the increase in $\bar{n}_e$? and (2) from where do the particles responsible for the density and Γ increase come? As noted above, even if there is no increase in $\bar{n}_e$ there is an increase in Γ. Hence $\Delta\Gamma$ may be the cause, but not the effect of $\Delta\bar{n}_e$. One possibility is that $\Delta\Gamma$ causes desorption of hydrogen from the walls and that this increases $\bar{n}_e$. Of course, both $\Delta\Gamma$ and the rise in $\bar{n}_e$ could be due to a third parameter's change.

The second question is answered conclusively. Of the three possible locations of the $\Delta\Gamma$ source - the walls, the antennae and the limiters - the increase in Γ comes from the walls. The limiter as source was eliminated by consideration of Fig. 7. The increase in Γ with the auxiliary limiter inserted in the plasma was additive not multiplicative. That the antennae are not the source was shown by puffing gas in near the antennae. A doubling of $\bar{n}_e$ in 50 ms by this means did not result in even a 10% increase in Γ.

The cause of $\Delta\Gamma$ is not an increase in the central ion density nor an increase in the charge exchange rate coefficient. Instead it is an increase in the neutral density. The following model is proposed to explain the increase in Γ:

The underlying cause of $\Delta\Gamma$ is a rise in the ion density at the wall, as shown schematically in Fig. 8. The increased edge ion density leads to an increased neutralization of ions on the wall and to increased desorption and therefore a higher edge neutral density. A high edge density means more charge exchange with the plasma ions and therefore a higher neutral efflux (observed by the LENS). The increase in ion density at the wall required to explain $\Delta\Gamma$ is rather small. If we assume that the perpendicular transport velocity of the protons is about $v_\perp \simeq 10^4$ cm/s, the usual value[15,19] for ions in the edge plasma, then the edge ion density need only rise

$$\Delta n_i(a) \simeq \Delta\Gamma / v_\perp = 10^{11}\ \mathrm{cm}^{-3}.$$

An alternative explanation is that v increases. However, earlier Langmuir probe experiments on ATC[20], and more recent ones on PLT[21], both showed an increase in ion saturation current, hence ion density, during ICRF heating. Yet another explanation for the increased ion density is a higher ionization rate, as could be caused by a higher $T_e(a)$. This has not yet been ruled out.

Mechanisms possibly responsible for an increased outflux include electron plasma waves, cyclotron resonances or stochastic transport. Similarly, the relative importance of these cannot yet be judged.

The increased interaction of ICRF-heated plasmas with the torus wall indicate the need for detailed studies of plasma behaviour versus plasma (or limiter) to wall separation. Perhaps by this means we can control $\Delta\Gamma$ and thus control the rise in $\bar{n}_e$ and the rise in impurity levels can be controlled.

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Figure Captions

Fig. 1. Schematic view of PLT showing the position of the LENS diagnostic relative to the limiters and ICRF antennae.

Fig. 2. Flux of charge exchange particles at a position away from the limiters. Application of ICRF power occurred between 350 and 500 ms.

Fig. 3. Flux spectra, $d\Gamma/dE$, during ICRF heating. Also shown is $d\Gamma/dE$ for a unheated discharge. The energy range is 20-1000 eV.

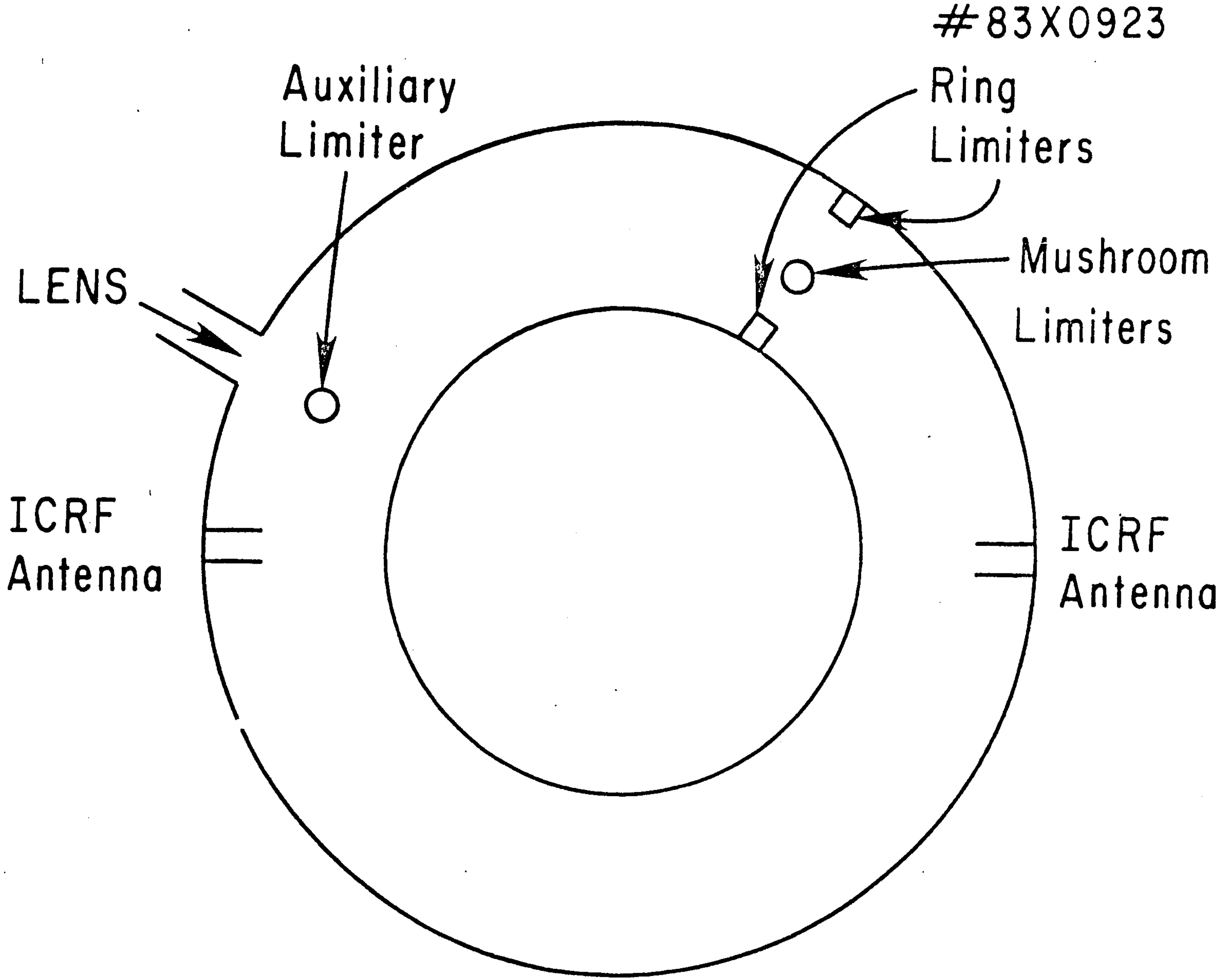
Fig. 4. Same as for figure 3, but the the energy range is 20-200 eV.

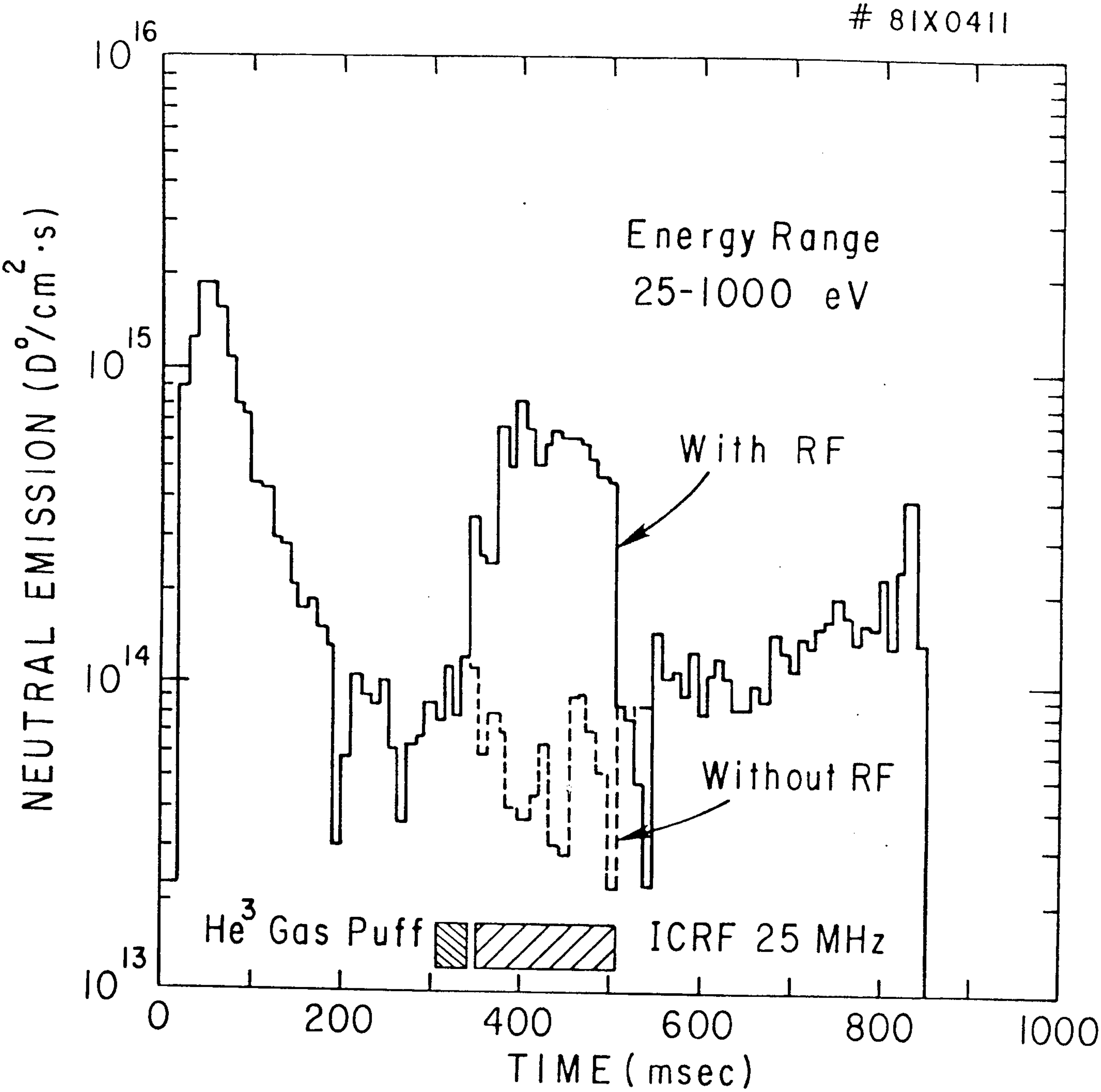
Fig. 5. Change in flux, $\Delta\Gamma$, versus applied ICRF power. The 25 MHz coil system was used for heating a D-He^3 plasma.

Fig. 6. Change in flux, $\Delta\Gamma$, versus plasma current I_p, for an applied power of 520 kW.

Fig. 7. Change in neutral outflux due to application of ICRF and the insertion of an auxiliary limiter in the same gap as the LENS system.

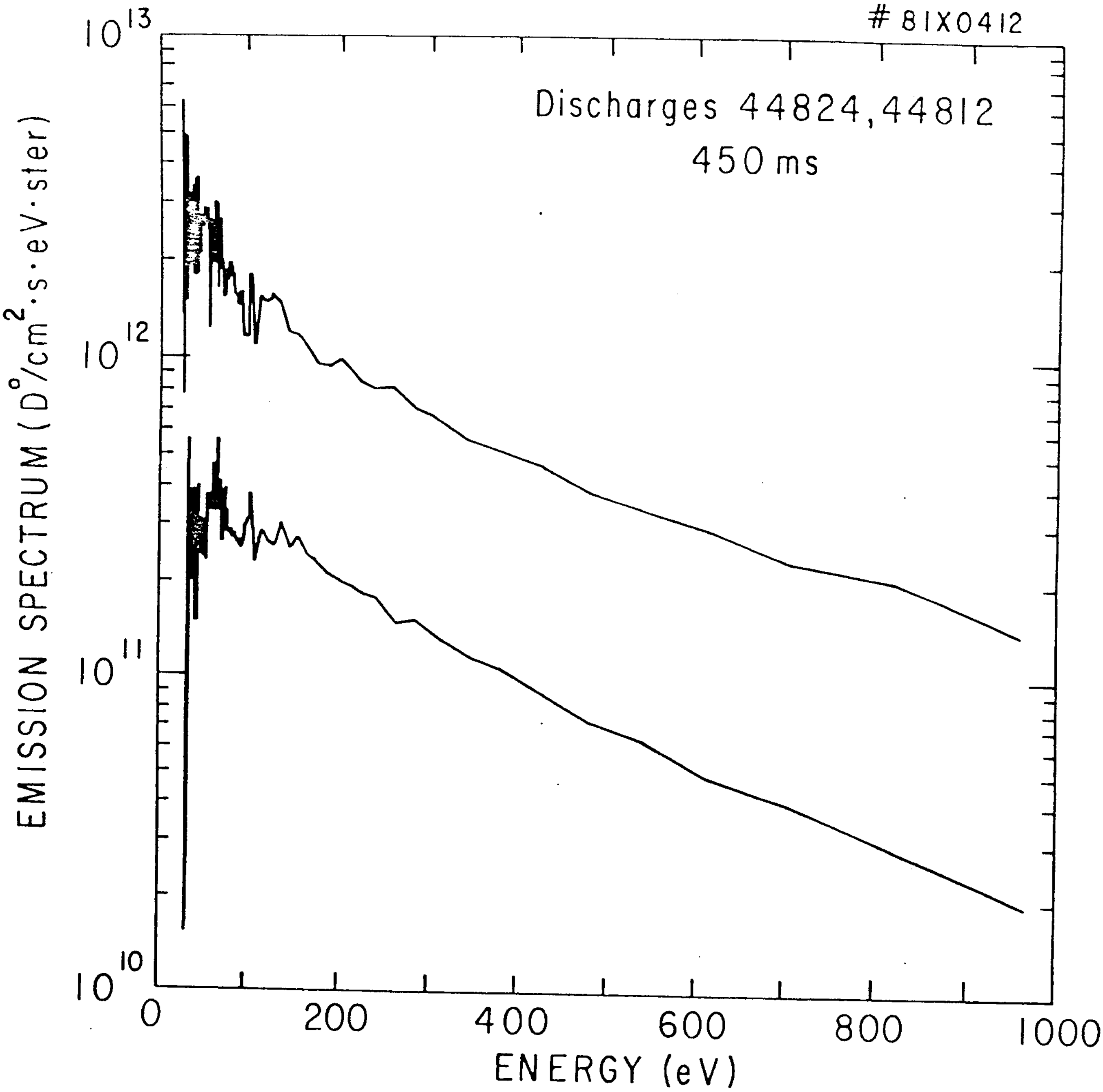
Fig. 8. Model for the increase in neutral outflux. The application of RF increases the ion density near the wall. This increases the number of neutrals born at the wall and subsequently the charge exchange.


#83X0923
Auxiliary
Limiter
Ring
Limiters
LENS
Mushroom
Limiters
ICRF
Antenna
ICRF
Antenna



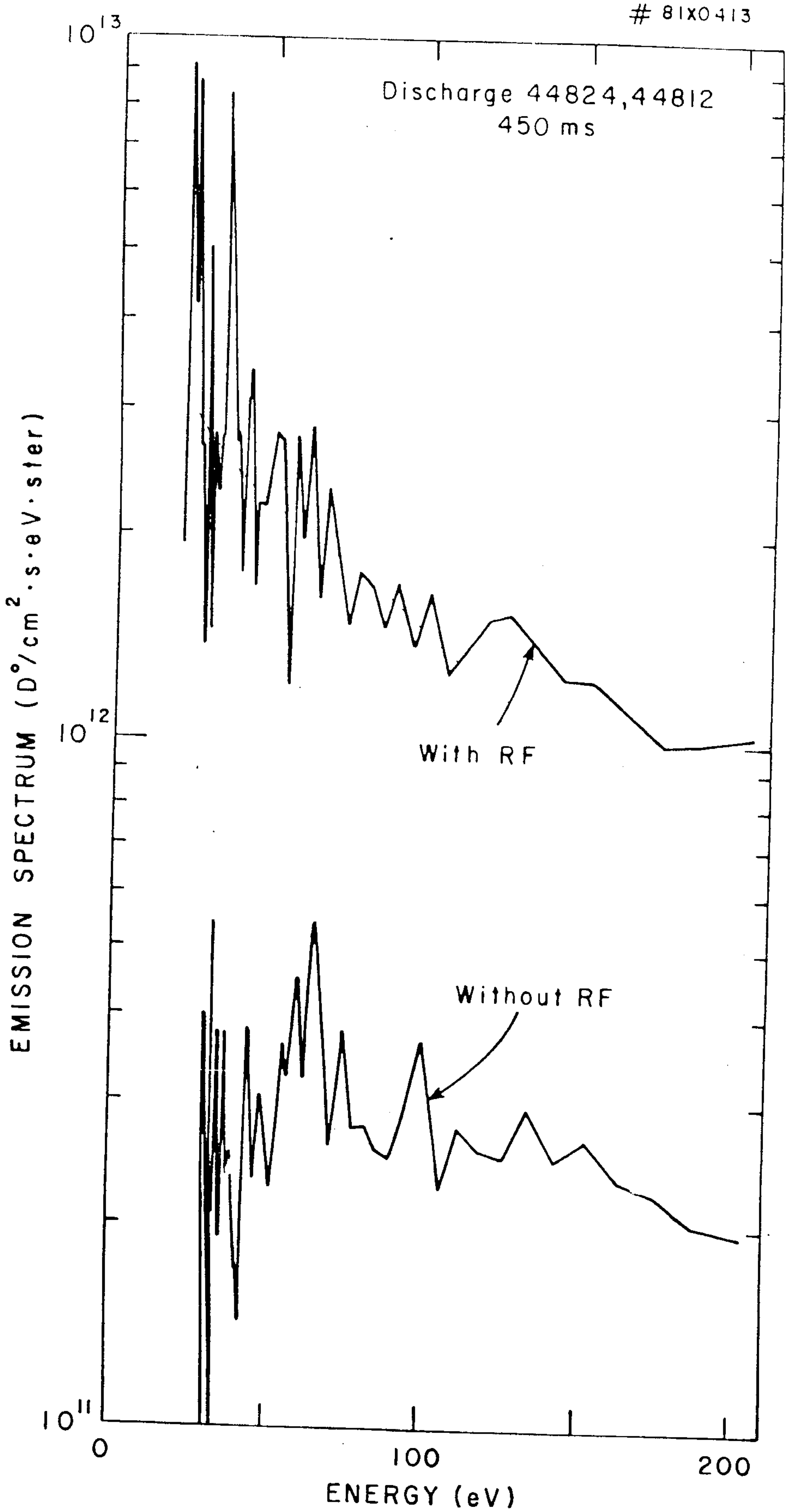
81X0411
Energy Range
25-1000 eV
With RF
Without RF
He3 Gas Puff
ICRF 25 MHz
NEUTRAL EMISSION (D°/cm2·s)
TIME (msec)
10^16
10^15
10^14
10^13
0
200
400
600
800
1000

Fig. 3



81X0412
Discharges 44824, 44812
450 ms
EMISSION SPECTRUM (D°/cm²·s·eV·ster)
10^13
10^12
10^11
10^10
0
200
400
600
800
1000
ENERGY (eV)

Fig. 3



81X0413
Discharge 44824,44812
450 ms
With RF
Without RF
EMISSION SPECTRUM (D°/cm² · s · eV · ster)
10^13
10^12
10^11
0
100
200
ENERGY (eV)

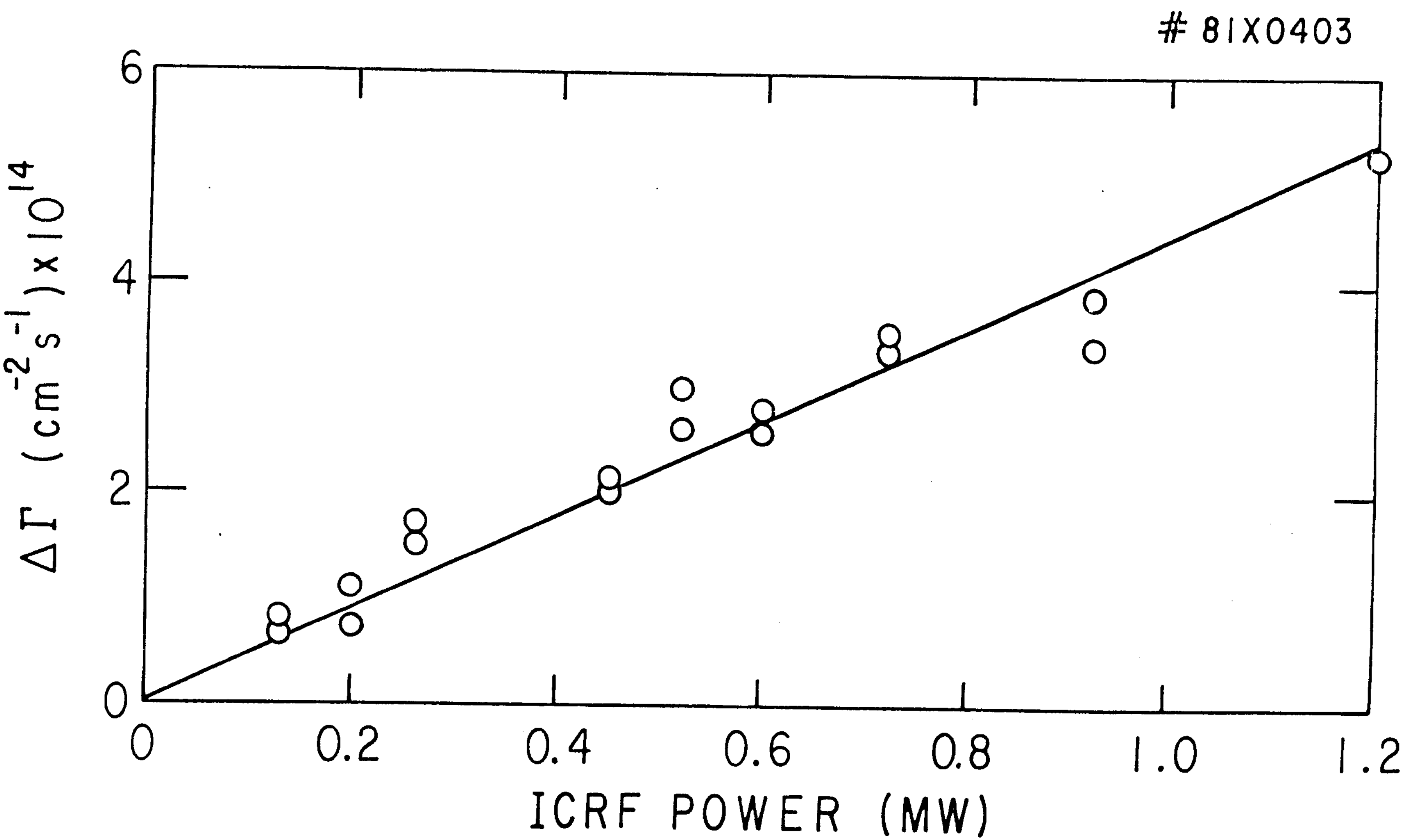


Fig. 5

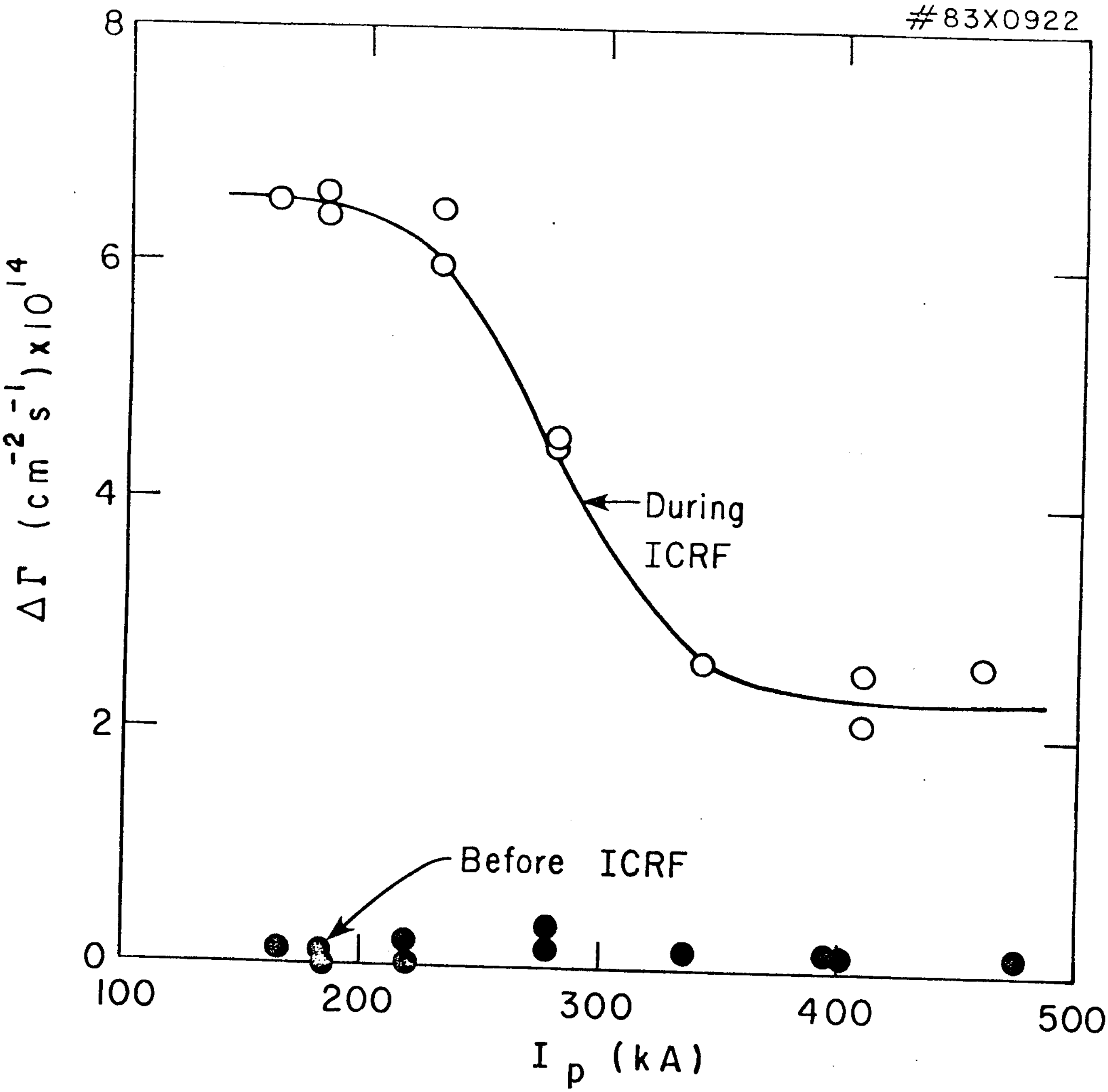

#83X0922
8
6
4
2
0
ΔΓ (cm^{-2}s^{-1})x10^{14}
During
ICRF
Before ICRF
100
200
300
400
500
I$_p$ (kA)

Fig. 6

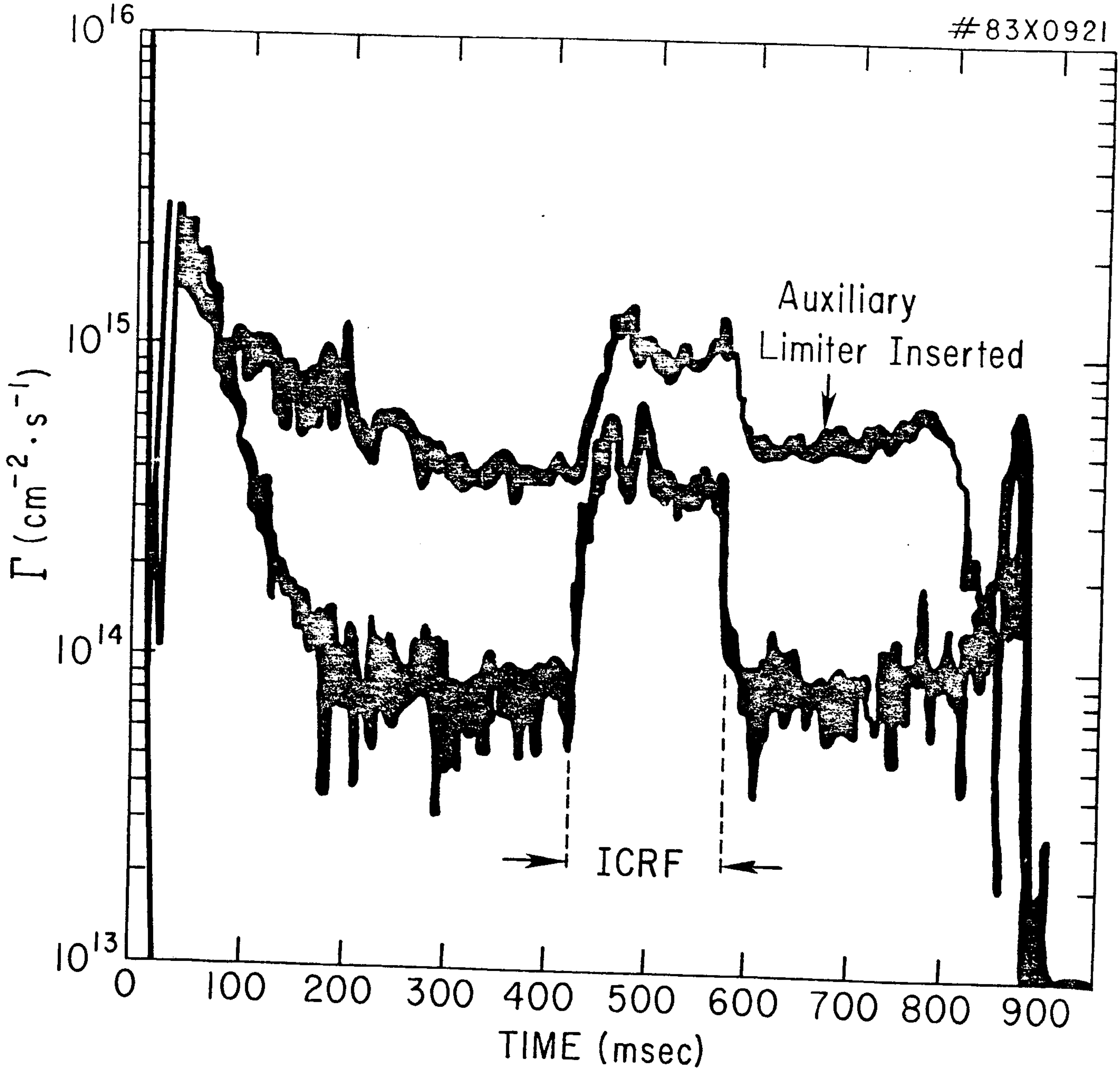

#83X0921
10^{16}
10^{15}
10^{14}
10^{13}
Γ (cm⁻²·s⁻¹)
Auxiliary
Limiter Inserted
ICRF
0
100
200
300
400
500
600
700
800
900
TIME (msec)

Fig. 7

81X0404

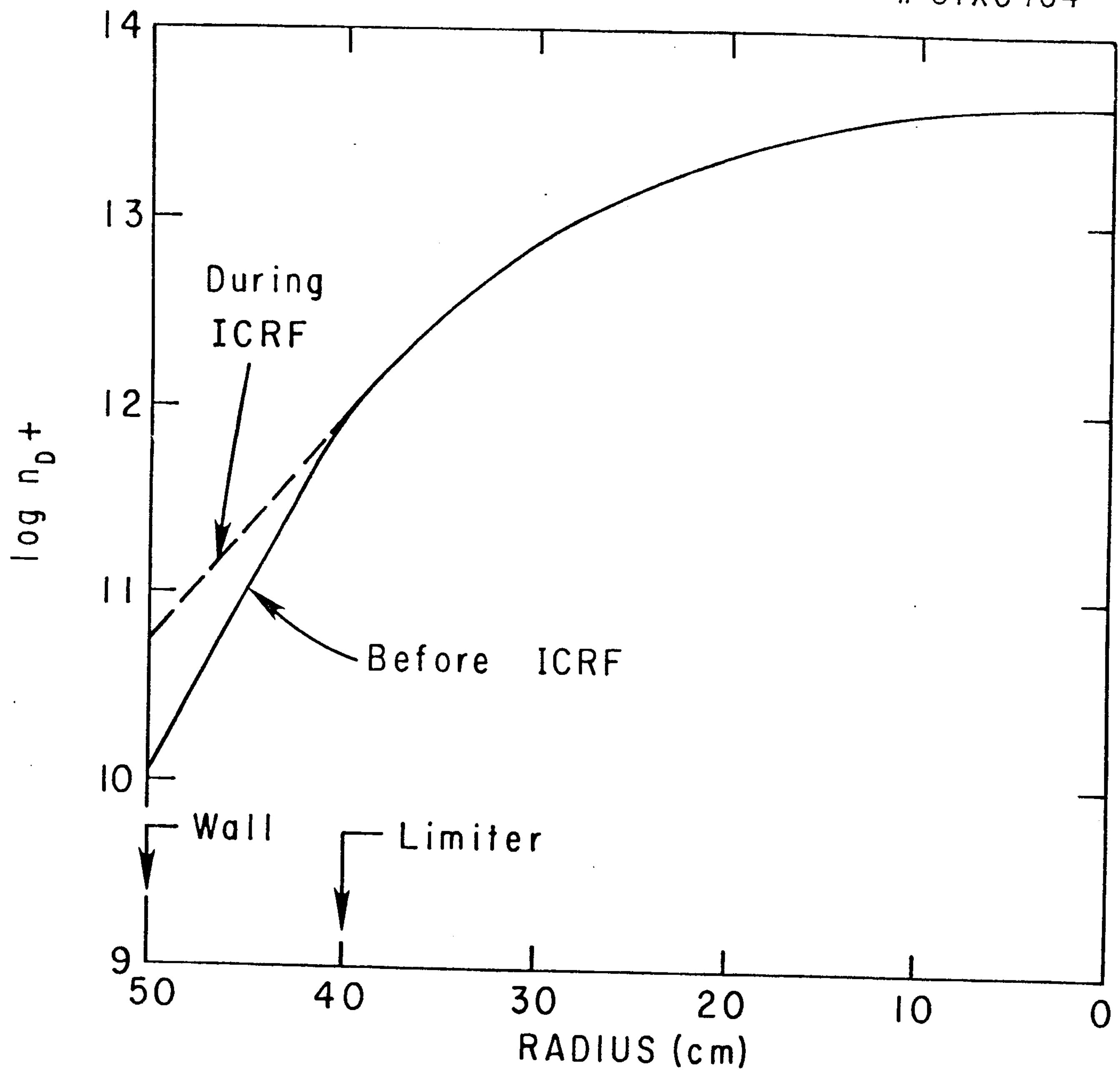


Figure 2